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ON 11 CM IRREGULARITIES DURING EQUATORIAL SPREAD F.(U)
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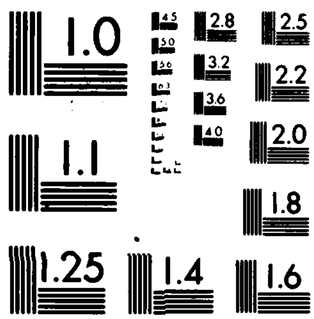

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The recent Kwajalein radar backscatter observations of 11 cm irregularities at high altitudes (~500 km) during equatorial spread F are explained in terms of the kinetic lower-hybrid-drift instability. The absence of radar backscatter from 11 cm irregularities at lower altitudes (~240 km) is attributed to the stabilizing influence of electron-neutral collisions.

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CONTENTS

ON 11 CM IRREGULARITIES DURING EQUATORIAL SPREAD F

I. Introduction

During the past several years, high-frequency radar backscatter experiments have revealed a spectrum of short-wavelength (i.e., below the ion gyroradius) irregularities during equatorial spread F (ESF). Radar backscatter observations at 50 MHz, 155 MHz and 415 MHz indicate density fluctuations exist with scale sizes of 3m, 1m and 36 cm, respectively [Farley et al., 1970; Woodman and LaHoz, 1976; Costa and Kelley, 1978a,b; Huba et al., 1978]. Most recently, Tsunoda (1980) has observed radar backscatter from 11 cm (1320 MHz) irregularities during equatorial spread F at high altitudes, using the TRADEX radar. These observations were part of a coordinated Defense Nuclear Agency campaign at Kwajalein to study ionospheric irregularities during equatorial spread F. The program was designed to obtain simultaneous radar backscatter results and in situ rocket measurements of density and fluctuating fields. Unfortunately, the 11 cm observations were made prior to the rocket launch (but during ESF), so coincidental in situ plasma and fluctuation data are not available. However, presumably ionospheric plasma conditions were similar during the various measurements.

Sharp density gradients were observed during this campaign (M. C. Kelley, private communication, 1980) and have been observed during past equatorial spread F events (Costa and Kelley, 1978a,b). The scale lengths of these gradients range from tens of meters to several hundred meters and are presumably due to primary longer wavelength instabilities such as the Rayleigh-Taylor instability. Since the typical ion gyroradius is $r_{Li} \sim 5$m, it is found that $r_{Li}/L_n \leqslant 0.2$ where L_n is the density gradient scale length. Based upon this evidence, it has been suggested that various drift instabilities are responsible for the short wavelength irregularities [Huba et al., 1978; Costa and Kelley, 1978a,b; Huba and Ossakow, 1979a,b], depending upon

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the wavelength observed. Although collisionless drift waves would easily be excited under these circumstances, collisional effects have a stabilizing influence on the instabilities investigated thus far [Huba and Ossakow, 1979a,b; Sperling and Goldman, 1980]. Specifically, the lower-hybrid-drift instability is the prime candidate to explain the 1m, 36 cm and 11 cm irregularities. However, recent work [Huba and Ossakow, 1979a; Sperling and Goldman, 1980] has indicated that electron-electron, electron-ion and electron-neutral collisions stabilize the instability and an approximate threshold condition has been derived [Sperling and Goldman, 1980].

In the light of the new observations of 11 cm irregularities and theoretical results, we show that the lower-hybrid-drift instability is the most probable cause of the small-scale irregularities (i.e., 11 cm, 36 cm and 1m) observed during equatorial spread F. Moreover, we discuss the role of these irregularities on the large scale plasma behavior during these periods.

II. Theory

We consider a plasma immersed in a homogeneous, unidirectional field $\underset{\sim}{B} = B_o \hat{e}_z$ with an inhomogeneous density profile $n = n(x)$ and a constant temperature ($T_e = T_i = T$). Each species α (i.e., electrons and O^+ ions) has a diamagnetic drift velocity $\underset{\sim}{V}_{d\alpha} = (v_\alpha^2/2\Omega_\alpha)\ d\ \ell n\ n/dx$ where $v_\alpha = (2T_\alpha/m_\alpha)^{1/2}$ is the thermal velocity, $\Omega_\alpha = e_\alpha B_o/m_\alpha c$ is the cyclotron frequency and $n = n_e \approx n_i$. A net current exists in the plasma $\underset{\sim}{J}_o = en(V_{di} - V_{de})\hat{e}_y \approx 2en\ V_{di}\ \hat{e}_y$ which provides the free energy to drive an instability. Perturbed quantities are assumed to vary as $\exp[iky - i\omega t]$ and we consider only electrostatic oscillations since $\beta \ll 1$. We make use of the local approximation which requires $kL_n \gg 1$ where $L_n = (d\ \ell n\ n/dx)^{-1}$ is the density gradient scale length. The ions are taken to be unmagnetized while the electrons are

considered to be magnetized. The ions behave as unmagnetized particles for the wavelengths under consideration ($k\, r_{Li} \sim 10^2$) because of ion-ion collisions (Huba and Ossakow, 1979a). Electron-neutral, electron-electron and electron-ion collisions are included in the analysis via an effective collision frequency $\nu_e = \nu_{en} + \nu_{ei}\,(1 + 0.15\, k^2 r_{Le}^2)$ where $r_{Le} = v_e/|\Omega_e|$ is the mean electron Larmor radius (Kadomtsev, 1965; Sperling and Goldman, 1980). We note that our coefficient of $k^2 r_{Le}^2$ differs from that of Sperling and Goldman (1980) due to a different definition of the thermal velocity.

Based upon these assumptions, we obtain the following dispersion equation for the lower-hybrid-drift instability

$$D(\omega,k) = 1 + \chi_i + \chi_e \tag{1}$$

where (Huba et al., 1978)

$$\chi_i = \frac{2\omega_{pi}^2}{k^2 v_i^2}\left[1 + \frac{\omega - kV_{di}}{kv_i}\; Z\left(\frac{\omega - kV_{di}}{kv_i}\right)\right] \tag{2}$$

and (Sperling and Goldman, 1980)

$$\chi_e = \frac{2\omega_{pe}^2}{k^2 v_e^2}\left[1 - \frac{\omega - kV_{de} + i\nu_e}{\omega + i\nu_e}\; \Gamma_o(b_e)\right]\left[1 - \frac{i\nu_e}{\omega + i\nu_e}\; \Gamma_o(b_e)\right]^{-1} \tag{3}$$

where $\omega_{p\alpha}^2 = 4\pi n_\alpha e_\alpha^2/m_\alpha$, $v_\alpha^2 = 2T_\alpha/m_\alpha$, $\Omega_\alpha = e_\alpha B_o/m_\alpha c$, $V_{d\alpha} = (v_\alpha^2/2\Omega_\alpha) d\, \ell n\, n/dx$, $\nu_e = \nu_{en} + \nu_{ei}(1 + 0.3\, b_e)$, $b_e = k^2 r_{Le}^2/2$, $\Gamma_o(x) = I_o(x)e^{-x}$, I_n is the modified Bessel function of order n and Z is the plasma dispersion function. We note that Eq. (3) is based upon the BGK collision model and, strictly speaking, does not correctly treat electron-electron collisions (Rukhadze and Silin, 1968). However, electron viscosity is approximately modeled via the term proportional to $k^2 r_{Le}^2$ (Mikhailovskii and Pogutse, 1966). Since the 11 cm irregularities correspond to $kr_{Le} \approx 2$, it is clear that electron viscous effects are only moderately important. Moreover, the BGK model is adequate

in the absence of temperature gradients (Rukhadze and Silin, 1968) which is the situation in the F region. Thus, Eq. (3) can be used with confidence to describe the electron response qualitatively. The quantitative results based upon Eq. (3) are approximately correct since a model Fokker Planck equation is used to describe the collisionality.

Since $V_{di} \ll v_i$ (which corresponds to $r_{Li} \ll L_n$), we can expand the plasma dispersion function in the small argument limit (i.e., $Z(\psi) \approx i\sqrt{\pi}$). The dispersion equation assumes the form

$$D(\omega,k) = 1 + \frac{2\omega_{pi}^2}{k^2 v_i^2}\left[1 + i\sqrt{\pi}\,\frac{\omega - kV_{di}}{kv_i}\right]$$
$$+ \frac{2\omega_{pe}^2}{k^2 v_e^2}\left[1 - \frac{\omega - kV_{de} + i\nu_e}{\omega + i\nu_e}\,\Gamma_o(b_e)\right]\left[1 \quad \frac{i\nu_e}{\omega + i\nu_e}\,\Gamma_o(b_e)\right]^{-1} = 0. \tag{4}$$

In the limit $\gamma \sim \nu_e \ll \omega_r$, where $\omega = \omega_r + i\gamma$, Eq. (4) has the following solution

$$\omega_r = \Gamma_o\, kV_{di}\left[1 + k^2\lambda_{di}^2 + (T_i/T_e)(1-\Gamma_o)\right] \tag{5}$$

$$\gamma = -\,\omega_r(\omega_r/kV_{di})\left[\frac{\sqrt{\pi}}{\Gamma_o}\,\frac{\omega_r - kV_{di}}{kv_i} + \frac{T_i}{T_e}\,\frac{\nu_e}{\omega_r}\,(1-\Gamma_o)\left(1 + \frac{kV_{di}}{\omega_r}\,\frac{T_e}{T_i}\right)\right] \tag{6}$$

where $\lambda_{di}^2 = v_i^2/2\omega_{pi}^2$ and the argument of Γ_o has been suppressed. In the absence of collisions ($\nu_e = 0$), instability occurs for $\omega_r < kV_{di}$ and there is no threshold requirement. However, electron collisions are stabilizing and place a threshold condition on the drift velocity to excite the mode (Huba and Ossakow, 1979a; Sperling and Goldman, 1980). Substituting Eq. (5) into Eq. (6), the critical drift velocity (i.e., such that $\gamma > 0$) is given by

$$\left(\frac{V_{di}}{v_i}\right)_{cr} > \left[\frac{\nu_e}{\Omega_i}\left(\frac{m_e}{m_i}\right)^{1/2}\frac{1}{\sqrt{\pi}}\;\frac{(1-\Gamma_o)}{kr_{Le}\Gamma_o}\;\frac{(2+k^2\lambda_{di}^2 - \Gamma_o)^2(2+k^2\lambda_{di}^2)}{2(1-\Gamma_o) + k^2\lambda_{di}^2}\right]^{1/2} \tag{7}$$

This corresponds to a critical density gradient scale length via $L_n^{cr} < (v_i/V_{di})_{cr}\ (r_{Li}/2)$.

We now apply Eq. (7) to plasma conditions relevant to equatorial spread F to determine whether or not the lower-hybrid-drift instability is responsible for the 11 cm radar backscatter observations. We choose B = 0.3 G, $T_e = T_i = 0.1$ eV and $m_i = 16\ m_p$. The collision frequency is given by

$$\nu_e = \nu_{en} + \nu_{ei}(1 + 0.15\ k^2 r_{Le}{}^2) \tag{8}$$

where (Braginskii, 1965; Johnson, 1961)

$$\nu_{en} = 5.0 \times 10^{-8}\ n_n T_e^{1/2}\ \mathrm{sec}^{-1} \tag{9}$$

$$\nu_{ei} = (\lambda/3.5 \times 10^5)(n_e/T_e{}^{3/2})\ \mathrm{sec}^{-1} \tag{10}$$

and n_n is the neutral density, n_e is the electron density $\lambda = 23.4 - 1.15 \log n_e + 3.45 \log T_e$, and T_e is given in eV. We plot $(V_{di}/v_i)_{cr}$ and L_n^{cr}(meters) versus kr_{Le} in Fig. 1 for the following values: $n_e = 10^4, 10^5, 10^6\ \mathrm{cm}^{-3}$ and $n_n = 10^8, 5 \times 10^9\ \mathrm{cm}^{-3}$. The range in electron density corresponds to the ambient density ($n_e \sim 10^6 \mathrm{cm}^{-3}$) to the density within ionospheric bubbles or plasma depletions ($n_e \sim 10^4 \mathrm{cm}^{-3}$). The values of the neutral density are for altitudes of 500 km ($n_n \sim 10^8 \mathrm{cm}^{-3}$) and 240 km ($n_n \sim 5 \times 10^9 \mathrm{cm}^{-3}$) during sunspot maximum (Johnson, 1961). The altitude of 500 km corresponds to the region from which the 11 cm radar backscatter returns were observed (Tsunoda, 1980); whereas, the 240 km altitude corresponds to the bottom of the F region on that same night. Also, we have marked the values of kr_{Le} which correspond to 1m, 36 cm and 11 cm, respectively. Several interesting features of Fig. 1 are as follows.

First, minimum values of $(V_{di}/v_i)_{cr}$ and L_n^{cr} exist for $kr_{Le} \sim 0.6$ as noted by Sperling and Goldman (1980). The minimum is rather broad for low n_e but becomes sharper as n_e is increased. This indicates that for a given density and density gradient scale length only a certain range of kr_{Le} can be excited linearly. Second, larger values of the neutral density require larger drift velocities (or shorter density gradient scale lengths) as expected. This is a more dramatic effect at lower electron densities ($n_e \sim 10^4 cm^{-3}$) than higher electron densities ($n_e \sim 10^6 cm^{-3}$) simply because ν_{ei}/ν_n scales as n_e. And finally, for $n_e = 10^4 cm^{-3}$ there is a cutoff at $kr_{Le} \approx 1.5$. This arises because $k\lambda_{de} \approx 1$ for these values and one does not expect collective plasma phenomena to occur on length scales shorter than a Debye length. Thus, for electron densities less than $10^4 cm^{-3}$, there will be no density fluctuations with scale lengths shorter than 20 cm other than thermal fluctuations.

III. Discussion

Recently, during a coordinated ground-based rocket campaign to study ionospheric irregularities during equatorial spread F at Kwajalein, Tsunoda (1980) observed radar backscatter from 11 cm irregularities. These are the smallest scale irregularities observed thus far and are comparable to the mean electron Larmor radius ($r_{Le} \sim 3$ cm). An important feature of the experimental results is that these irregularities were only observed at high altitudes ($\sim$ 500 km). During the rocket flight, which occurred subsequent to the 11 cm radar backscatter measurements, in situ probes detected sharp density gradients ($L_n \geqslant 45$m; Kelley, private communication, 1980) and large density depletions ($n_e \sim$ several x $10^4 cm^{-3}$; E. Szuszczewicz, private communication, 1980) at high altitude ($\sim$ 500 km). We note that previous in situ rocket measurements have found density gradient scale lengths as small as 30m (Costa and Kelley, 1978a).

These data suggest the following scenario. As equatorial spread F develops, density depletions rise to the topside of the F region where the neutral density is low ($\sim$ 500 km). Within these plasma bubbles (where electron collisional effects are minimal) sharp density gradients exist which can excite the lower-hybrid drift instability. The density fluctuations associated with the instability give rise to the radar backscatter measurements at 1m, 36 cm and 11 cm. This can occur for $L_n \geqslant 20m$, $n_e < 10^5 cm^{-3}$ and $n_n \sim 10^8 cm^{-3}$ (see Fig. 1) which is consistent with observational results to within a factor of two. This is quite good considering the approximations involved in deriving the electron response (Eq. (3)). At lower altitudes (< 250 km) the increased neutral density requires a sharper density gradient scale length for a given value of n_e (or lower values of n_e for fixed density gradient scale length) especially for the 11 cm irregularities (see Fig. 1) and the mode is stable. Also, it is possible that the density within the lower altitude density depletions is $n_e \leqslant 10^4 cm^{-3}$ and radar backscatter is not observed at 11 cm since this is smaller than the Debye length. Thus, based upon the linear theory of the lower-hybrid-drift instability, it is found that this mode is the most probable cause of the small-scale irregularities ($\leqslant$ 1m) observed during equatorial spread F.

Finally, we discuss the role of this instability in the evolution of the large scale plasma phenomena occurring during equatorial spread F. Typically, plasma microturbulence influences the plasma via its anomalous transport properties (i.e., scattering of particles by the collective fields associated with the instability). A recent theoretical study of the lower-hybrid-drift instability (Drake, 1980) indicates that this mode can only produce irreversible electron heating and diffusion when $e\phi/T \geqslant 0.2$-0.5 where ϕ is the fluctuating electrostatic potential. To produce this level

of turbulence requires very sharp density-gradients ($L_n \leqslant r_{Li}$) which do not exist during equatorial spread F. For typical ionospheric conditions (i.e., $L_n \gg r_{Li}$), the instability will saturate at a low level of turbulence and not be an effective anomalous transport mechanism. Thus, the small-scale density and field fluctuations associated with this mode are a signature of equatorial spread F (under the proper conditions) and will probably not significantly influence the macroscopic fluid evolution of the plasma for scale sizes $\geqslant$ Ln.

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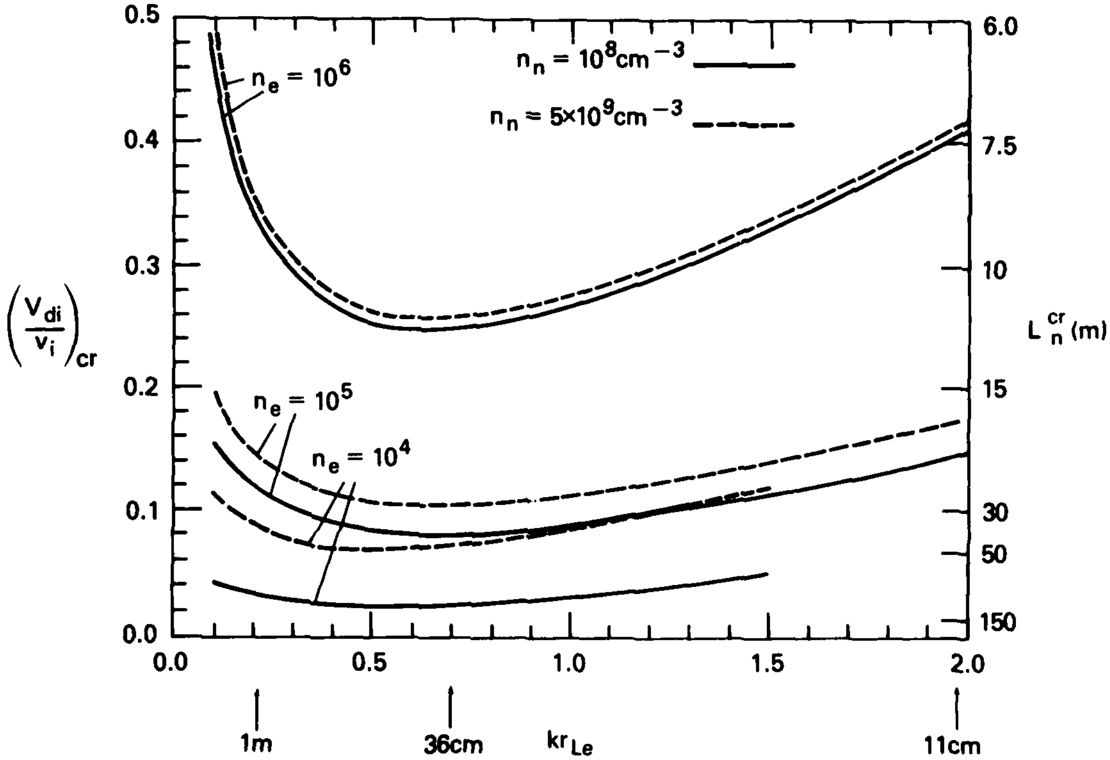

Fig. 1 — Plot of $(V_{di}/v_i)_{cr}$ and L_n^{cr} (meters) vs. k r_{Le}. Values of V_{di}/v_i and L_n above the curves lead to instability, while those below lead to stability. The following densities are considered: electron density ($n_e = 10^4, 10^5, 10^6 cm^{-3}$) and neutral density ($n_n = 10^8 cm^{-3}$ and $n_n = 5 \times 10^9 cm^{-3}$...).

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